

Hot Jupiters and Super-Earths

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Abstract

We explore the role of dynamics in shaping planetary system multiplicities, focussing on two particular problems. **(1)** We propose that the lack of close-in super-Earths in hot Jupiter systems is a signature of the migration history of the hot Jupiters and helps to discriminate between different mechanisms of migration. We present N-body simulations of dynamical migration scenarios where proto-hot Jupiters are excited to high eccentricities prior to tidal circularisation and orbital decay. We show that in this scenario, the eccentric giant planet typically destroys planets in the inner system, in agreement with the observed lack of close super-Earth companions to hot Jupiters. **(2)** We explore the role of the dynamics of outer systems in affecting the multiplicities of close-in systems such as those discovered by *Kepler*. We consider specifically the effects of planet–planet scattering and Kozai perturbations on an exterior giant planet on the architecture of the inner system, and evaluate the ability of such scenarios to reduce the inner system’s multiplicity and contribute to the observed excess of single *Kepler* planets.

1 High-eccentricity migration of hot Jupiters destroys inner planets

The formation and migration of hot Jupiters has been discussed since their discovery. Migration may take place at early times on a near-circular orbit in a protoplanetary disc (Lin et al. 1996; Ward 1997). Alternatively, migration may occur after protoplanetary disc dissipation, as the giant planet’s orbital eccentricity is excited to high values and then the orbit is re-circularised by tidal forces, shrinking the planet’s semi-major axis in the process (Rasio & Ford 1996). Several means of eccentricity excitation are possible, such as planet–planet scattering (Rasio & Ford 1996; Chatterjee et al. 2008) and various classes of secular perturbation (Wu & Murray 2003; Fabrycky & Tremaine 2007; Wu & Lithwick 2011; Beaugé & Nesvorný 2012; Petrovich 2015a,b).

The dynamical architecture of hot Jupiter systems may help to distinguish these two migration pathways. The high-eccentricity migration route requires that the hot Jupiters have, or previously had, massive planetary or stellar companions on wide orbits, which appears to be supported by recent observations, with around 70% of hot Jupiters having such companions (Knutson et al. 2014; Ngo et al. 2015). In contrast, the frequency of low-mass, close-in companions to hot Jupiters appears to be very low. No such companions have been discovered by RV surveys, while none of the hot Jupiters in the original *Kepler* field has low-mass transiting planets, nor do they show TTVs that these planets may induce (Steffen et al. 2012). The sole exception to this pattern is WASP-47, a system where the giant planet (Hellier et al. 2012) pairs up with an additional wide-orbit giant (Neveu-VanMalle et al. 2015) and also possesses two low-mass companions discovered by K2 transit photometry (Becker et al. 2015).

At present then, hot Jupiters appear to only rarely possess close companions (Figure 1). This is despite the fact that small, close-in planets are very commonly observed both by *Kepler* transit photometry (Fressin et al. 2013) and RV surveys (Howard et al. 2010). If the formation and migration of hot Jupiters and the formation of close-in planets are uncorrelated processes, one would therefore expect that around half of all migrating hot Jupiters would interact with close-in planets *en route* to their final destination. Previous work has shown that migration through the gas disc is not completely efficient at destroying other planets or suppressing their formation (e.g., Mandell et al. 2007; Fogg & Nelson 2009; Ketchum et al. 2011; Ogiwara et al. 2014). Here we concentrate on the case of high-eccentricity migration, showing that during its phase of high eccentricity a giant that will become a hot Jupiter

is almost guaranteed to destabilise and destroy any small planets close to the star. Full details of our work can be found in Mustill et al. (2015).

1.1 Results

We conducted a series of N-body integrations using the BS algorithm in the MERCURY package (Chambers 1999). Our set-up was to take a *Kepler* triple-planet system on circular orbits (Kepler-18, Kepler-23, Kepler-58, Kepler-339; these roughly span the range of planetary radii of *Kepler* planets) and add to it an eccentric giant planet on a wide orbit. We explored pericentres of the giant from 0.01 au to 0.25 au, and semi-major axes from 1.25 au to 10 au. Hence, we ignore the evolution prior to eccentricity excitation—be it planet–planet scattering, Kozai perturbations from a binary or secular planet–planet interactions—and focus on the effects on the inner planets if that eccentricity is imposed at the beginning of the integration. The giant planets’ inclinations are assigned isotropically since mechanisms of exciting eccentricity often excite high inclinations too, while the inclinations of the inner planets are within 5° of the reference plane. Giant planets are released from apocentre.

The results are summarised in Figure 2. There are three broad classes of outcome: (1) The giant planet destroys the system of inner planets, usually forcing them into the star. More rarely the giant collides with one or more of the inner planets, which may lead to an observable enrichment of the planet’s core. (2) The giant planet is ejected by the inner planets. In this case the number of inner planets may be reduced as they are destabilised and merge from three to two or one survivor. Ejection of the giant is possible because when coming in from a very large apocentre, only a small kick at pericentre is needed to increase the apocentre still further, while the more tightly-bound inner planets do not experience such strong effects. Ejection is more common when the giant has a wider orbit or when the inner planets are comparatively more massive. (3) The giant and at least one inner planet coexist after the 1 Myr integration ends. This typically happens when the giant’s orbit is not initially overlapping any of the inner planets’, and almost never happens when the giant’s pericentre is small enough to permit subsequent tidal circularisation ($q \lesssim 0.04$ au).

The pericentres of the giants vary very little during their interaction with the inner planets, while their semimajor axes may change significantly. Many of our surviving giants will form hot Jupiters given sufficient time for tidal circularisation of their orbits, since their pericentres remain small. Giants with larger pericentres ($\gtrsim 0.1$ au) may still experience significant changes to their semimajor axes as they destroy the inner planets, with their orbits sometimes shrinking to ~ 0.5 au. In doing so they maintain small pericentres and high eccentricities (up to ~ 0.8). This is a region hard to populate through *in situ* scattering of giant planets (Petrovich et al. 2014), and these systems may have in the past had close-in super-Earths or Neptunes.

Our simulations show that the formation of systems similar to WASP-47, where the hot Jupiter ($P = 4.16$ d) is accompanied by low-mass planets on interior ($P = 0.79$ d) and exterior ($P = 9.03$ d) orbits, is almost impossible under high-eccentricity migration. At the end of our $\sim 30\,000$ integrations we find that 23 of the surviving giants have a low-mass companion on an exterior orbit. Most of these companions have been scattered onto wide orbits beyond ~ 1 au, and no giant has two companions as does WASP-47b. This system therefore seems to have undergone disc migration.

2 Dynamical effects on planetary system multiplicities

As we saw above, a giant planet intruding into a close-in system may be ejected, but its intrusion may result in the loss of one or more of the inner planets. Similarly, in many of our systems where the giant coexists with the inner system, the number of planets in the inner system has been reduced through induced instability. This motivates an investigation of the extent to which the dynamics of an outer planetary system can affect the multiplicity of *Kepler*-detectable systems close to the star.

This question of multiplicity is of particular interest as many studies suggest a “*Kepler* dichotomy” between systems of high multiplicity and singles (e.g., Johansen et al. 2012; Fang & Margot 2012). This may be a signature of formation (Dawson et al. 2015; Moriarty & Ballard 2015), internal instability (Pu & Wu 2015; Volk & Gladman 2015) or externally-induced instability (Mustill et al. 2016a). We explore the latter scenario here.

Simulations suggest that for every hot Jupiter formed via high-eccentricity migration, at least ten times as many fail, either colliding with the star or failing to acquire the necessary high eccentricity (e.g., Anderson et al. 2015). This suggests that a few tens of percent of outer systems may be dynamically active, and we investigate the effects

of this on close-in multiple systems. We explore two dynamical scenarios: scattering in systems of multiple giant planets (e.g., Rasio & Ford 1996; Chatterjee et al. 2008) and Kozai perturbations by a distant binary (e.g., Wu & Murray 2003; Fabrycky & Tremaine 2007).

For each of our scenarios we run 300 simulations each with a triple *Kepler* system drawn from a debiased population where its probability of being chosen is inversely proportional to the probability of seeing a triple transit. For our Kozai runs we assign each system a single outer giant planet between 1 and 10 au, and a stellar binary companion between 50 and 1000 au. The planets are on circular, near-coplanar orbits while the binaries have an isotropic inclination distribution and eccentricities drawn uniformly between 0 and 1. For our planet–planet scattering runs we place in each system four giant planets beyond 1 au with orbits squeezed sufficiently close to ensure instability within the short 10 Myr time of the integrations (Chatterjee et al. 2008). We incorporate post-Newtonian relativistic forces into MERCURY as these can significantly affect the dynamics, particularly for the Kozai scenario.

2.1 Results

In each set of simulations, we destabilise around 25% of our close-in triples systems. For our binary runs our initial set of 300 *Kepler* triples is reduced to 230 after 10 Myr, while for our scattering runs the number of survivors is 224. The survival of these systems is shown in Figure 3 for the binaries, where we see that destabilisation is more likely with more massive outer planets and in tighter binaries. In the binary case the inner planets are destabilised at roughly the same rate at all semi-major axes, whereas in the scattering case the wider inner systems are more likely to be disrupted. This is likely because the binary perturbations can drive planets to smaller pericentres more easily than can planet–planet scattering.

Although the overall rate of destabilisation is similar in both scenarios, the number of surviving inner planets in the destabilised systems differs. 34 of the 70 destabilised inner systems in the binary runs lost all their inner planets, with 11 being reduced to two and 25 to one planet. On the other hand, in the scattering runs only 9 out of 85 inner systems lost all their planets, while 34 were reduced to two and 33 to one. This is again likely due to the weaker perturbations felt in the scattering systems as the outer planets’ pericentres are harder to force to low values.

Further analysis of these cases is ongoing (Mustill et al. 2016a). We are studying the excitation of mutual inclinations amongst the inner planets, as well as investigating the possible role of destructive planet–planet collisions (Mustill et al. 2016b).

3 Conclusion

We see that the multiplicities of close-in planetary systems can be significantly affected by the dynamics of outer systems. This is seen very strongly in hot Jupiter systems, where high-eccentricity migration almost always results in the complete destruction of any pre-existing planets at ~ 0.1 au. The lack of close companions to most currently known hot Jupiters—with WASP-47b being the only exception—therefore currently supports a high-eccentricity, dynamical pathway for their migration. This will be tested further in the future as new space missions (CHEOPS, TESS, PLATO) will search many more hot Jupiter systems for close companions.

The effects of outer planets that fail to become hot Jupiters can also be significant. Our preliminary simulations reveal that $\sim 25\%$ of dynamically active outer systems would reduce the multiplicities of any inner planetary systems during planet–planet scattering or Kozai cycles. Thus, the destabilising effects of outer planets on inner systems may go some way towards resolving the “*Kepler* dichotomy”, although other effects are likely to play a role. The true extent of the disruptive influence of outer planets on inner systems will be clarified as the outer regions of planetary systems are studied by Gaia, GPI, SPHERE, and longer-baseline RV surveys.

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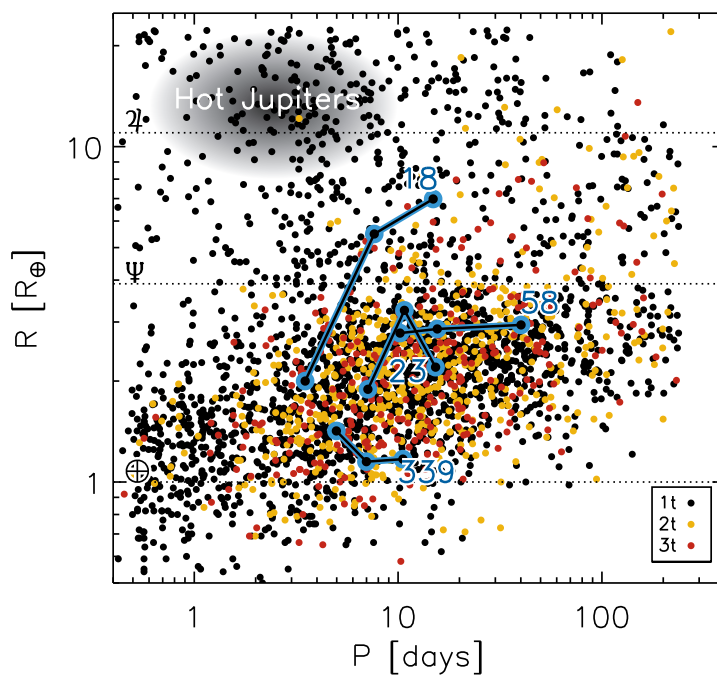


Figure 1: Periods and radii of *Kepler* single-, double- and triple-candidate systems. Hot Jupiters are single (top left of plot). Inner systems used as templates for further study are marked in blue.

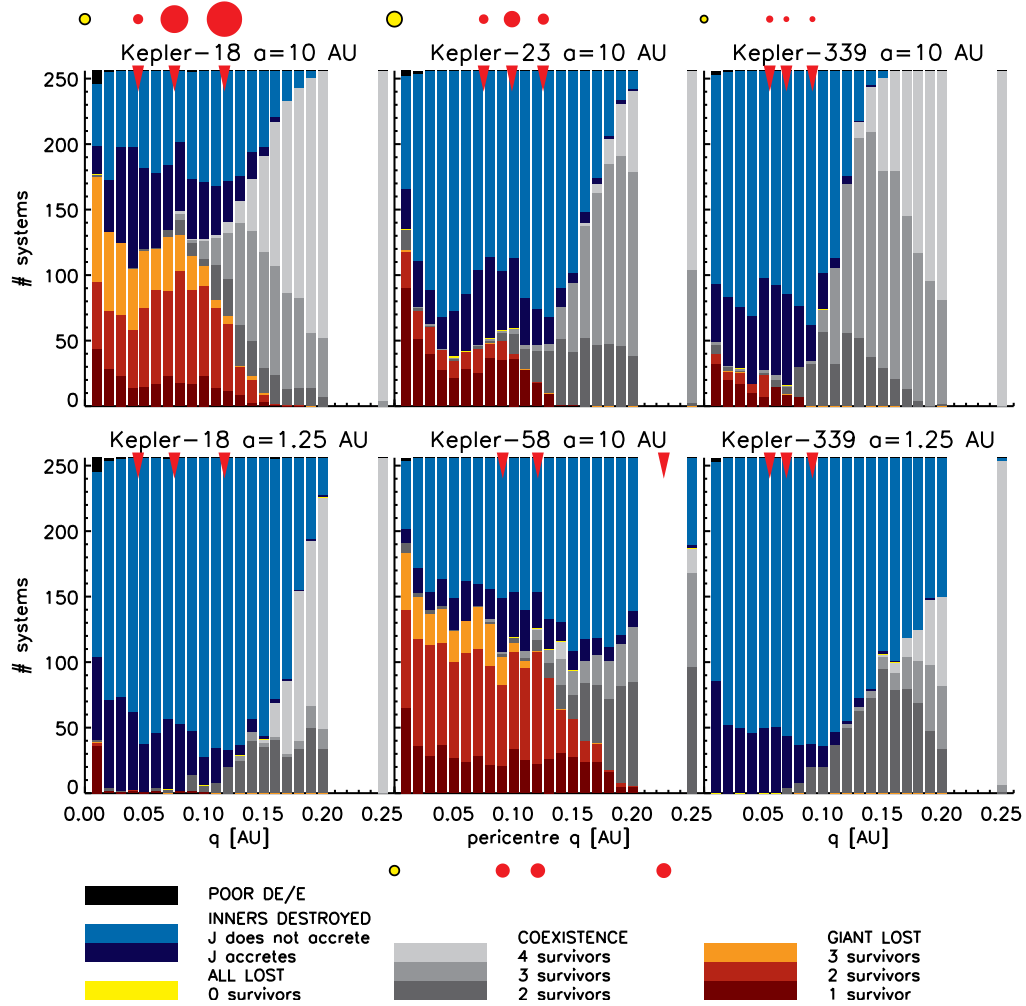


Figure 2: Stacked bar chart showing the effects of a highly-eccentric proto-hot Jupiter encountering inner planetary systems, for a variety of inner systems (shown above and below the bars), giant planet pericentres and semi-major axes. Each bar shows the outcome of a set of 256 simulations. Blue shows systems where the inner planets were destroyed, red/orange where the giant was lost and at least one inner planet survived. Grey shows where the giant and at least one inner planet survive for the 1Myr integration. Where the giant's pericentre is sufficiently small to permit later tidal circularisation ($\lesssim 0.04$ au), coexistence is highly unlikely and either the inner planets are destroyed (usually forced into the star) or the giant itself is lost (usually to ejection).

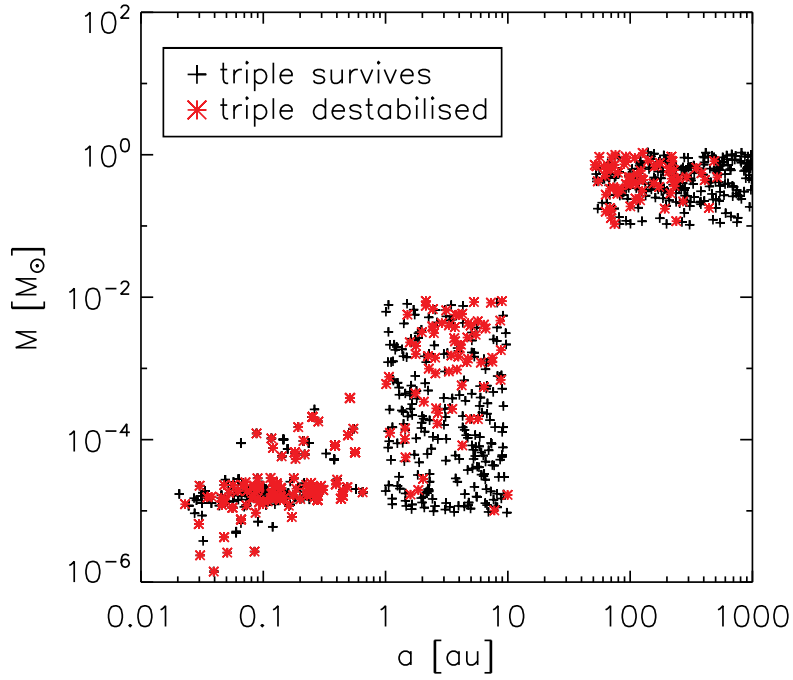


Figure 3: Effects of Kozai-perturbed giant planets on *Kepler* triple systems. Each integration comprises a triple system within 1 au, a giant planet between 1 and 10 au, and a binary star between 50 and 1000 au. Systems where one or more of the inner triple were lost are marked in red; those where they all survived, in black.